Model-Driven Verifying Compilation of Synchronous Distributed Applications

Sagar Chaki, James Edmondson
October 1, 2014

MODELS'14, Valencia, Spain

Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE **01 OCT 2014**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Model-Driven Verifying Compilation of Synchronous Distributed Applications**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Sagar Chaki James Edmondson**		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Software Engineering Institute Carnegie Mellon University Pittsburgh, PA 15213**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES **The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**24**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

This material is based upon work funded and supported by the Department of Defense under Contract No. FA8721-05-C-0003 with Carnegie Mellon University for the operation of the Software Engineering Institute, a federally funded research and development center.

DM-0001691

Outline

- Motivation
- Approach
- Sequentialization : SEQSEM & SEQDBL
- Examples
- Experimental Results
- Synchronizer Protocol : 2BSYNC
- Tool Overview & Demo
- Future Work

Motivation

Distributed algorithms have always been important

- File Systems, Resource Allocation, Internet, …

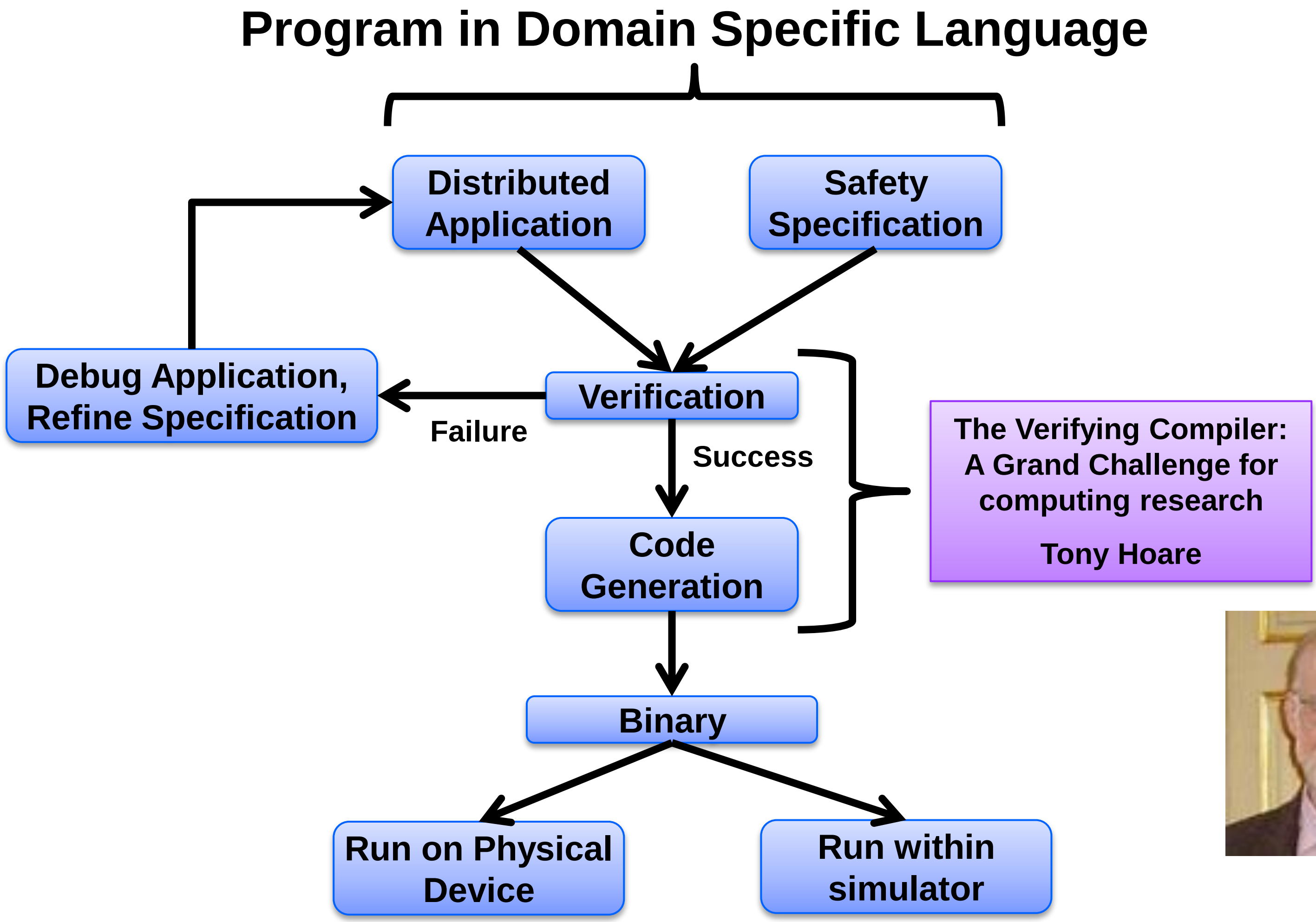
Increasingly becoming safety-critical

- Robotic, transportation, energy, medical

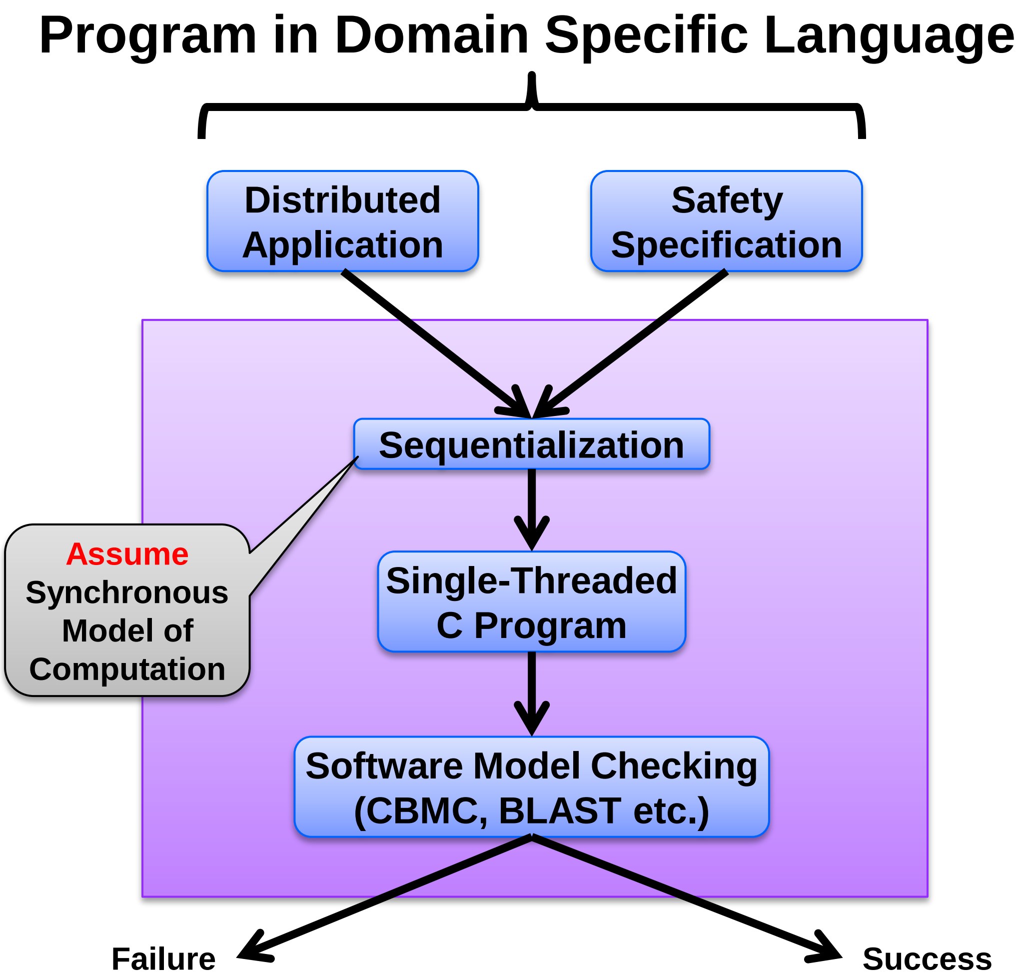
Prove correctness of distributed algorithm implementations

- Pseudo-code is verified manually (semantic gap)
- Implementations are heavily tested (low coverage)

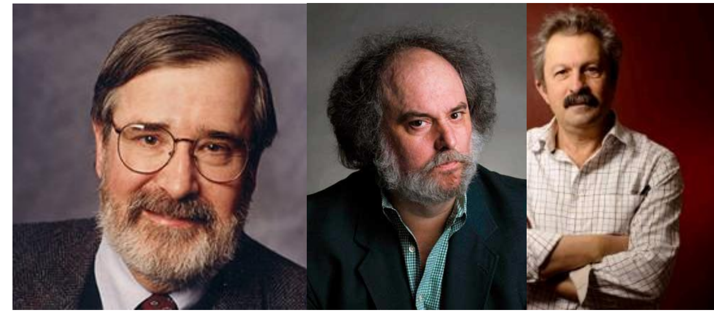
Approach : Verification + Code Generation



Verification



Model Checking



Automatic verification technique for finite state concurrent systems.

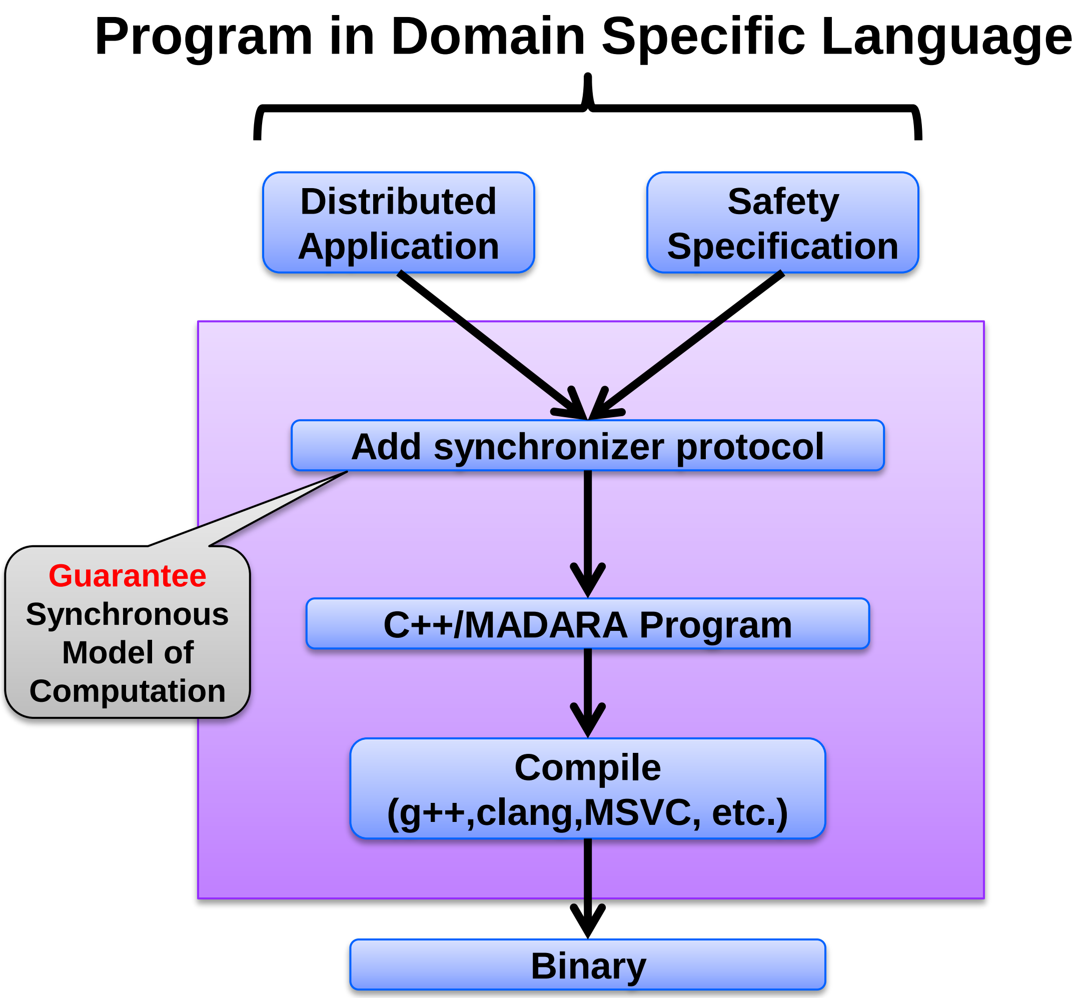
- Developed independently by Clarke and Emerson and by Queille and Sifakis in early 1980's.
- ACM Turing Award 2007

Specifications are written in propositional temporal logic. (Pnueli 77)

- Computation Tree Logic (CTL), Linear Temporal Logic (LTL), …

Verification procedure is an intelligent exhaustive search of the state space of the design

Code Generation



MADARA Middleware

A database of facts: $DB = Var \mapsto Value$

Node i has a local copy: DB_i

- update DB_i arbitrarily
- publish new variable mappings
  - Immediate or delayed
  - Multiple variable mappings transmitted atomically

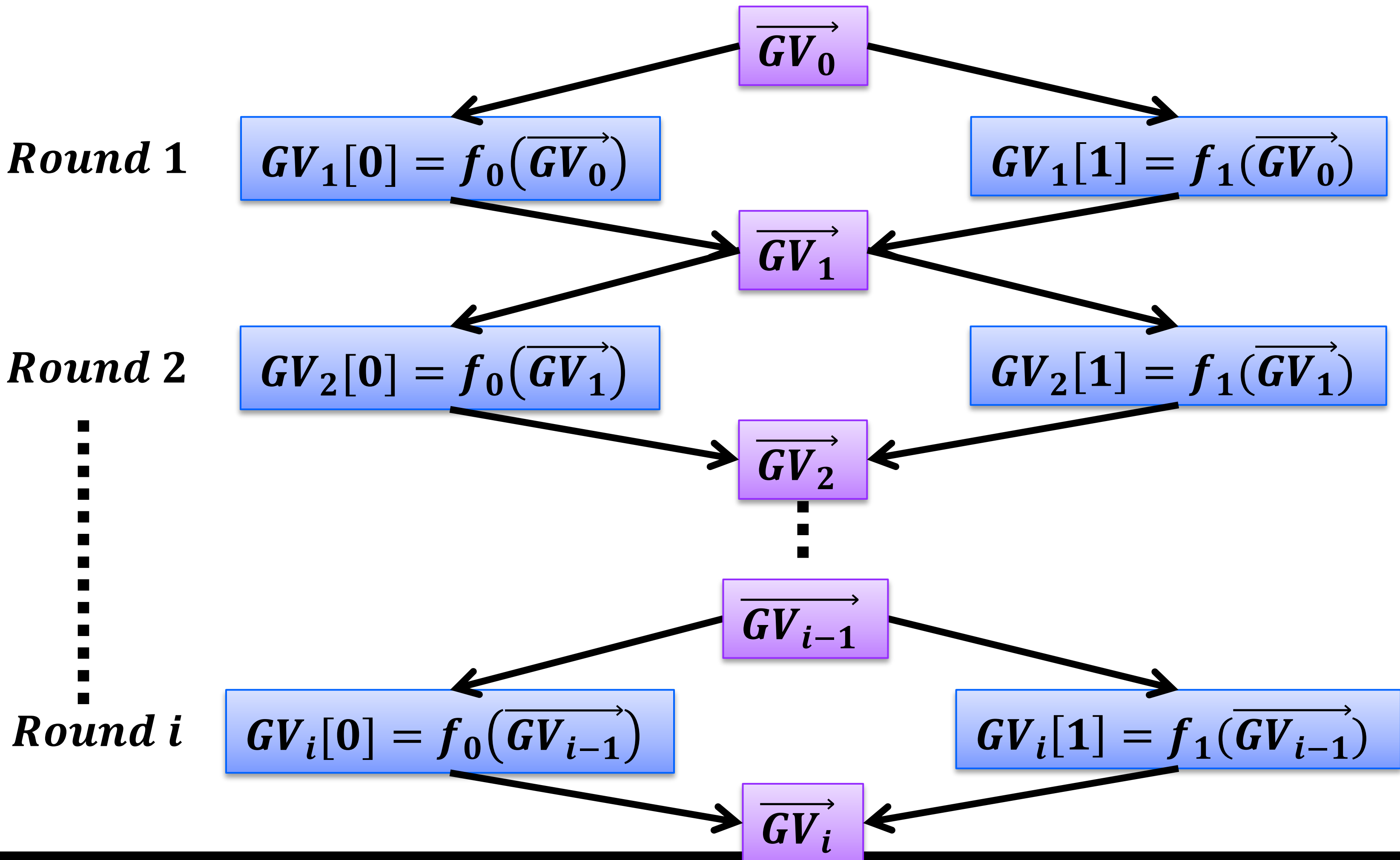
Implicit “receive” thread on each node

- Receives and processes variable updates from other nodes
- Updates ordered via Lamport clocks

Portable to different OSes (Windows, Linux, Android etc.) and networking technology (TCP/IP, UDP, DDS etc.)

Synchronous Distributed Application (SDA)

Node 0 $= f_0()$ Shared Variables: $\overrightarrow{GV} = GV[0], GV[1]$ Node 1 $= f_1()$



SDA Verification

Program with n nodes : $P(n)$

- Each node has a distinct $id \in [1, n]$
- Array GV has n elements, $GV[i]$ writable only by node with id i
- Each element of GV is drawn from a finite domain

In each round, node with id id executes function ρ whose body is a statement

$$
\begin{array}{lll}
stmt \coloneqq skip \mid lval = exp & & (assignment) \\
\quad \mid ITE(exp, stmt, stmt) & & (if, then, else) \\
\quad \mid ALL(IV, stmt) & & (iterate\ over\ nodes : use\ to\ check\ existence) \\
\quad \mid \langle stmt^{+} \rangle & & (iteration\ of\ statements) \\
lval \coloneqq GV[id][w] & & (lvalues) \\
exp \coloneqq \top \mid \bot \mid lval \mid GV[iv][w] \mid id \mid IV \mid \diamond(exp^{+}) & & (expressions)
\end{array}
$$

Initial states and “ERROR” states of the program are define

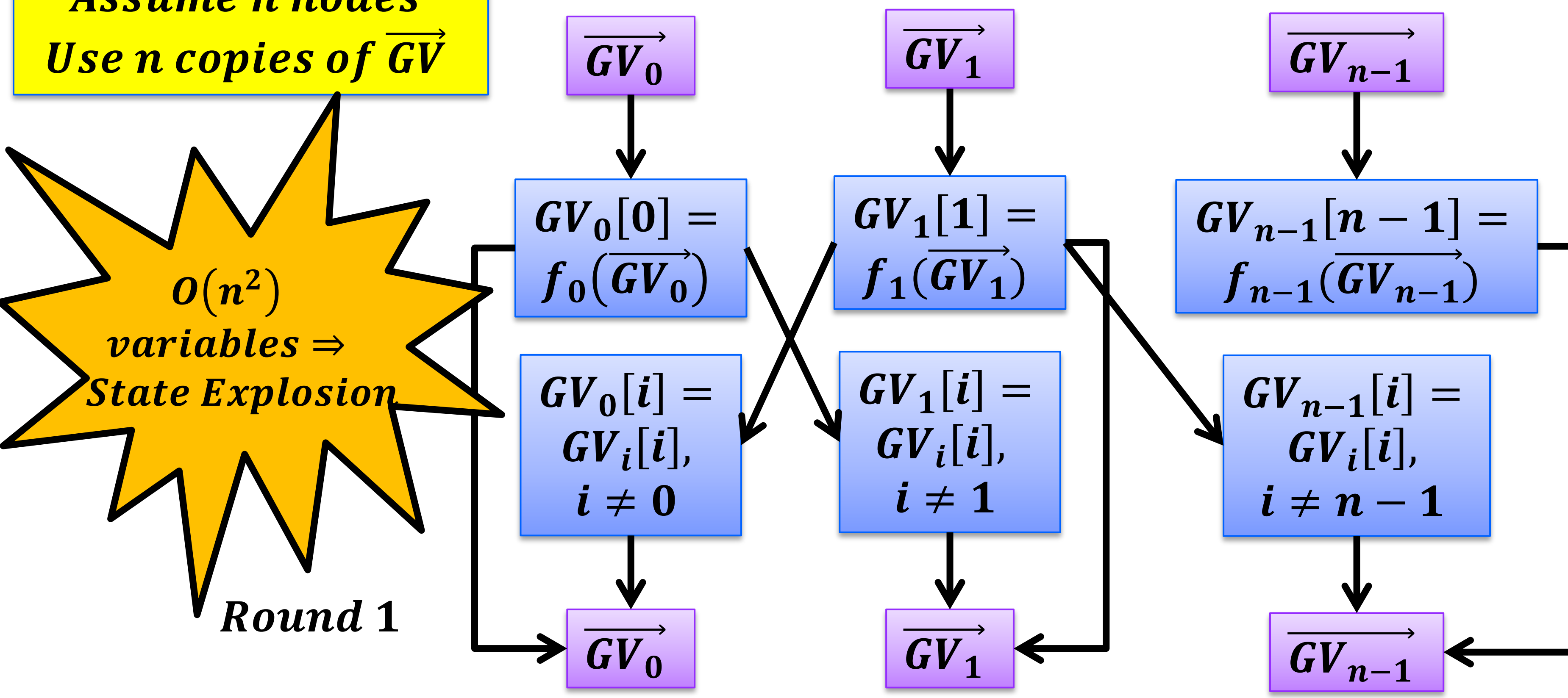
- State ≡ value assigned to all variables

Verification ≡ decide if there is an execution of the program that starts in an initial state and ends in an ERROR state

Semantic Sequentialization: SEQSEM

Node 0 $= f_0()$ Shared Variables: $\overrightarrow{GV} = GV[0], GV[1]$ Node 1 $= f_1()$

Assume n nodes
Use n copies of $\overrightarrow{GV}$



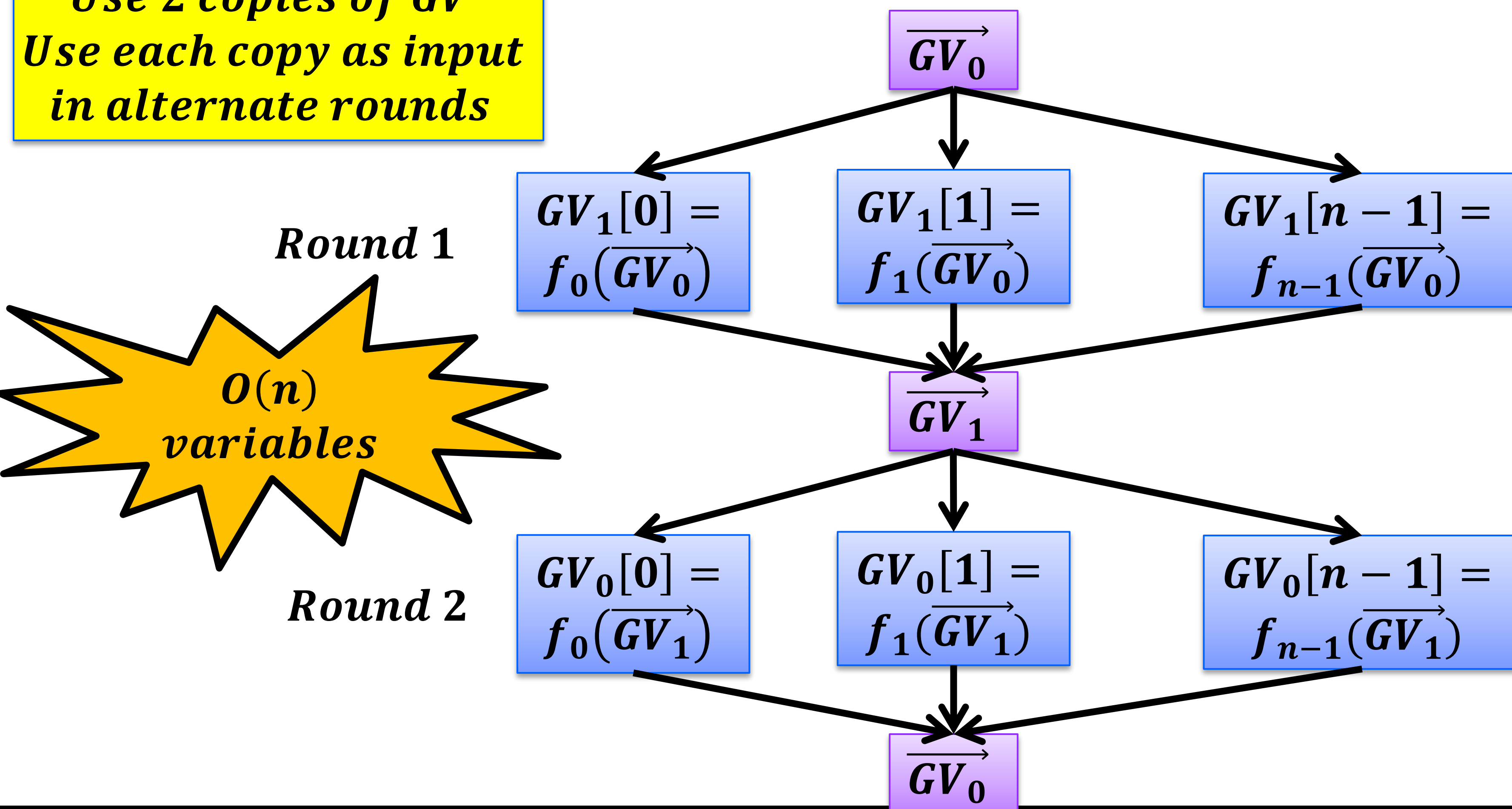
Operations have independentce $\Rightarrow$ reordered sequentially.

Rounds are repeated in a loop.

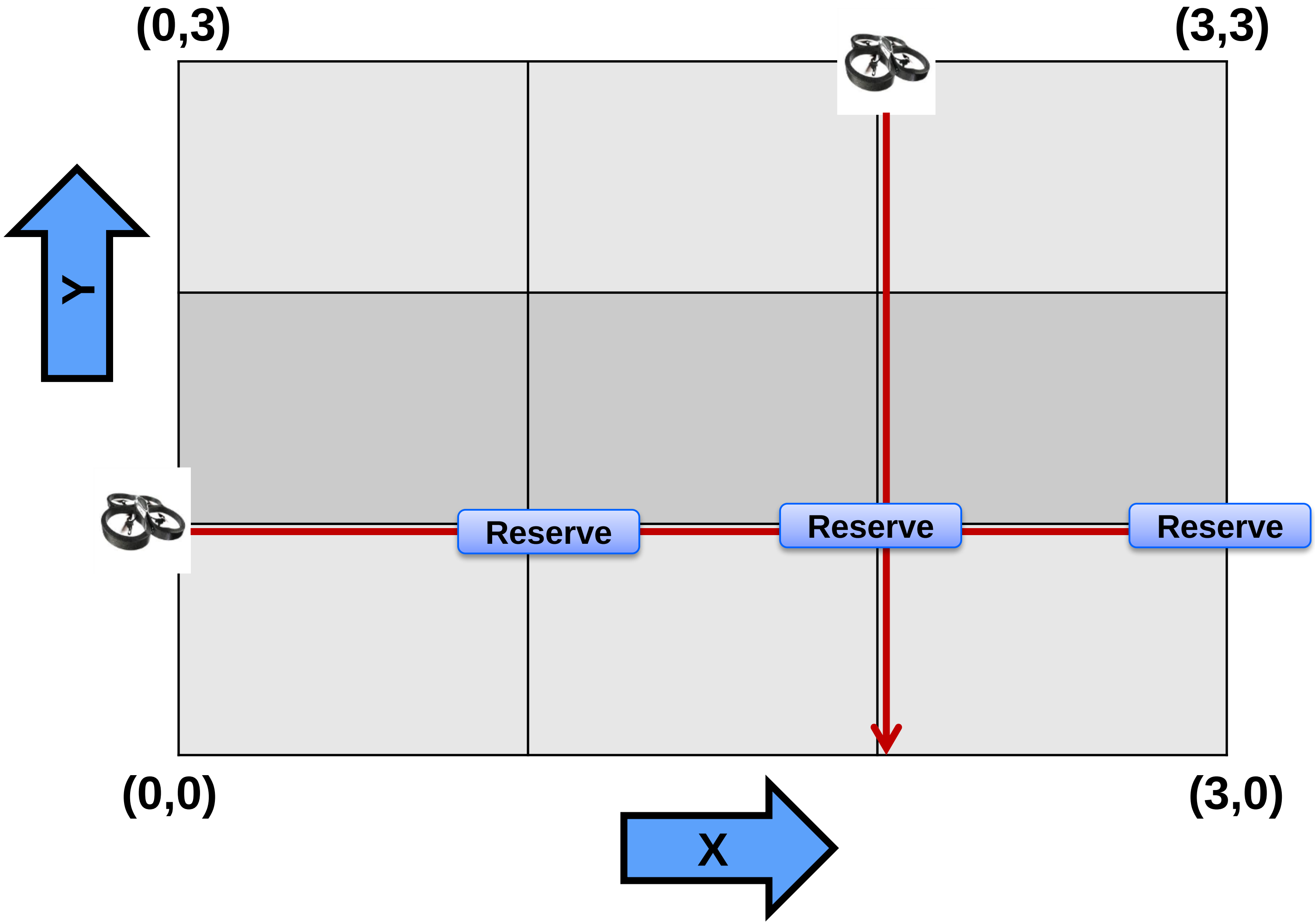
Double Buffering Sequentialization: SEQDBL

Node 0 $= f_0()$ **Shared Variables:** $\overrightarrow{GV} = GV[0], GV[1]$ **Node 1** $= f_1()$

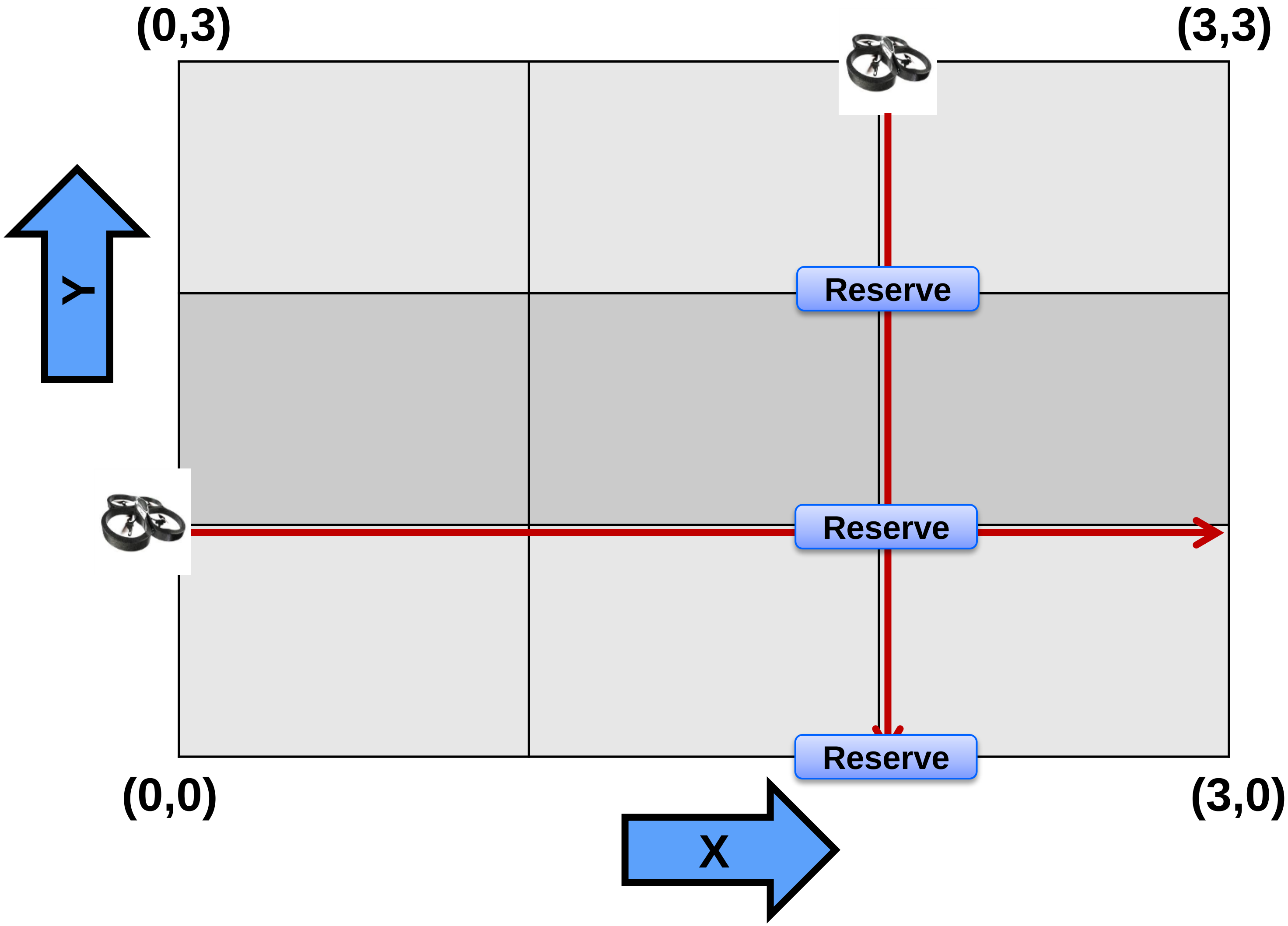
Use 2 copies of $\overrightarrow{GV}$
Use each copy as input in alternate rounds



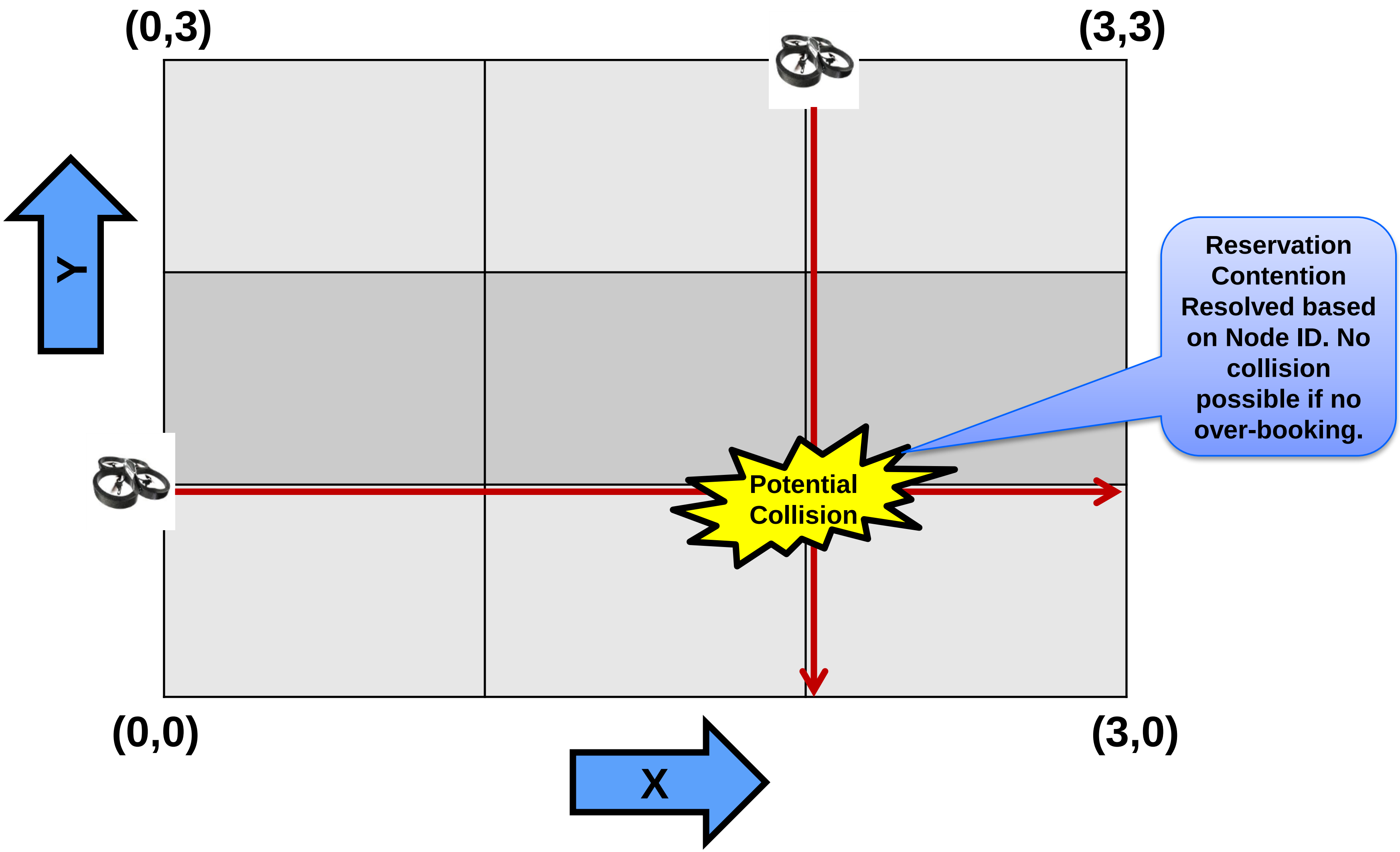
Example: 2D Synchronous Collision Avoidance



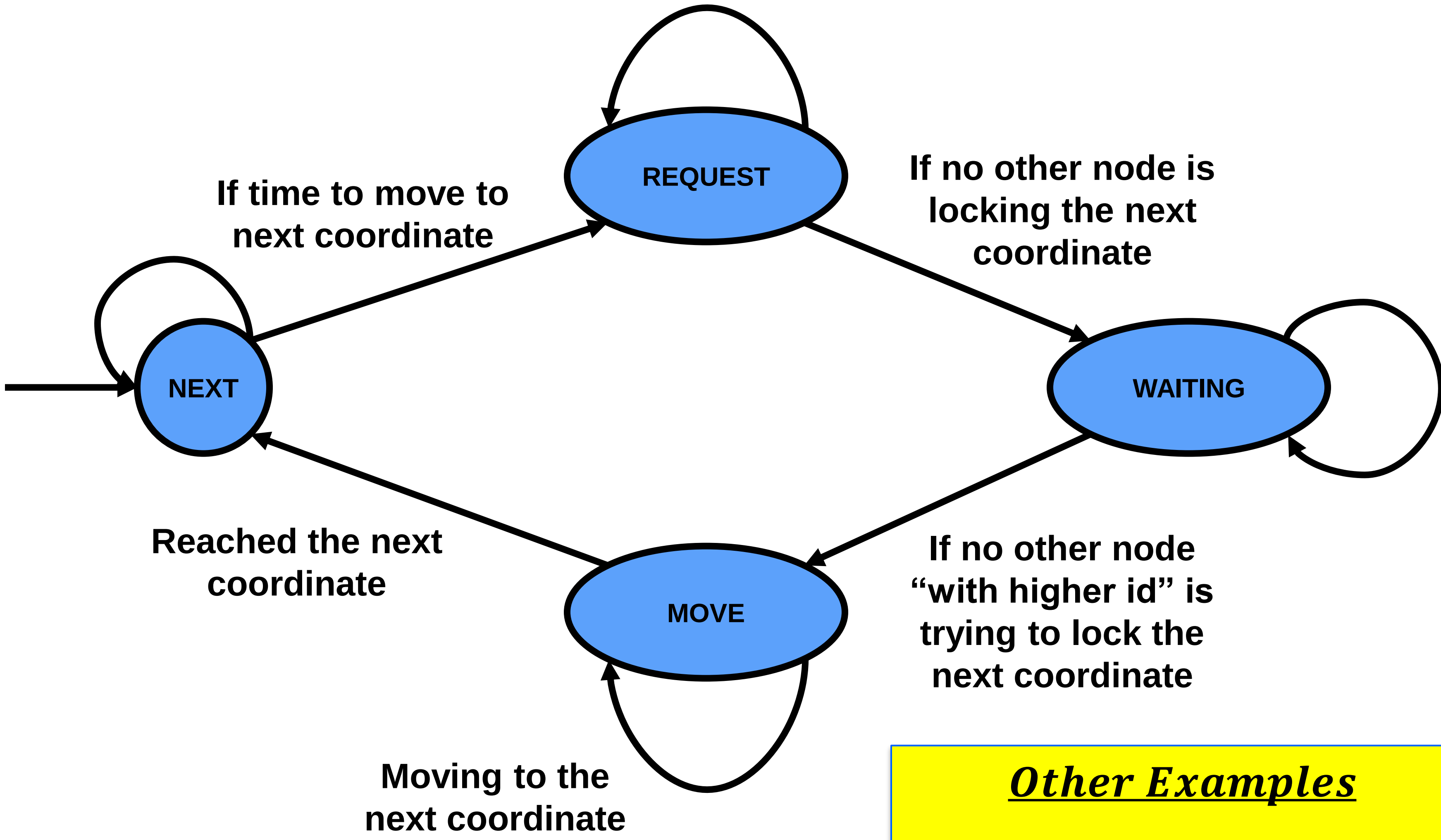
Example: 2D Synchronous Collision Avoidance



Example: 2D Synchronous Collision Avoidance



2D Collision Avoidance Protocol



Other Examples

3D Collision Avoidance

Mutual Exclusion

Results: 3D Collision Avoidance

3DCOLL-OK-4x4						
R	T_S	T_D	T_S	T_D	T_S	T_D
	$n=2$		$n=4$		$n=6$	
10	13	10	59	40	219	96
20	37	31	351	123	1014	480
30	48	48	406	202	–	–
	μ=2.213 σ=0.715					

3DCOLL-OK-7x7					
T_S	T_D	T_S	T_D	T_S	T_D
$n=2$		$n=4$		$n=6$	
31	35	323	148	1099	323
73	72	1262	401	–	–
142	113	–	–	–	–
μ=2.294 σ=0.763					

3DCOLL-BUG-4x4					
T_S	T_D	T_S	T_D	T_S	T_D
$n=2$		$n=4$		$n=6$	
8	9	49	36	123	96
24	36	119	101	410	210
42	44	206	155	–	–
μ=1.615 σ=0.425					

3DCOLL-BUG-7x7					
T_S	T_D	T_S	T_D	T_S	T_D
$n=2$		$n=4$		$n=6$	
22	23	194	114	–	–
57	76	–	–	–	–
117	134	–	–	–	–
μ=1.514 σ=0.344					

SEQDBL is better

T_S, T_D = model checking time with SEQSEM, SEQDBL

$$\mu, \sigma = Avg, StDev\ of\ \frac{T_S}{T_D}$$

n = #of nodes R = #of rounds $G \times G$ = grid size

Results: 2D Collision Avoidance

2DCOLL-OK-4x4						
R	T_S	T_D	T_S	T_D	T_S	T_D
	$n=2$		$n=4$		$n=6$	
10	17	25	87	262	280	831
20	123	271	1474	2754	–	–
30	863	1301	–	–	–	–
	μ=0.446 σ=0.118					

2DCOLL-BUG1-4x4					
T_S	T_D	T_S	T_D	T_S	T_D
$n=2$		$n=4$		$n=6$	
3	2	12	11	30	22
8	7	36	29	80	75
12	15	57	51	144	105
μ=1.282 σ=0.264					

2DCOLL-BUG2-4x4					
T_S	T_D	T_S	T_D	T_S	T_D
$n=2$		$n=4$		$n=6$	
4	3	13	11	30	29
8	9	33	33	76	66
16	21	57	77	150	120
μ=1.056 σ=0.266					

2DCOLL-OK-7x7						
R	T_S	T_D	T_S	T_D	T_S	T_D
	$n=2$		$n=4$		$n=6$	
10	74	146	395	1016	1707	–
20	1726	3096	–	–	–	–
30	–	–	–	–	–	–
	μ=0.598 σ=0.202					

2DCOLL-BUG1-7x7					
T_S	T_D	T_S	T_D	T_S	T_D
$n=2$		$n=4$		$n=6$	
7	7	32	24	101	70
15	22	94	55	345	150
40	35	180	91	–	223
μ=1.382 σ=0.517					

2DCOLL-BUG2-7x7					
T_S	T_D	T_S	T_D	T_S	T_D
$n=2$		$n=4$		$n=6$	
5	10	26	36	188	113
19	22	71	113	207	166
46	68	124	295	416	235
μ=0.906 σ=0.393					

Depends on the example

$T_S, T_D = \textit{model checking time with } SEQSEM, SEQDBL$

$\mu, \sigma = Avg, StDev \textit{ of } \frac{T_S}{T_D}$

$n = \#of\ nodes \quad R = \#of\ rounds \quad G \times G = grid\ size$

Results: Mutual Exclusion

MUTEX-OK						
R	T_S	T_D	T_S	T_D	T_S	T_D
	$n=6$		$n=8$		$n=10$	
60	406	396	1116	1051	2388	2268
80	850	806	2268	1967	4525	4249
100	1404	1381	3584	3452	7092	6764
	μ=1.040 σ=0.038					

MUTEX-BUG1					
T_S	T_D	T_S	T_D	T_S	T_D
$n=6$		$n=8$		$n=10$	
184	175	517	439	1068	959
402	372	1013	925	2203	1812
734	686	1726	1566	3513	3287
μ=1.056 σ=0.060					

SEQSEM and SEQDBL similar

MUTEX-BUG2					
T_S	T_D	T_S	T_D	T_S	T_D
$n=6$		$n=8$		$n=10$	
233	216	637	553	1292	1167
500	462	1218	1112	2602	2139
890	838	2056	1860	4216	3742
μ=1.065 σ=0.056					

$T_S, T_D = \textit{model checking time with SEQSEM, SEQDBL}$

$$\mu, \sigma = \textit{Avg, StDev of } \frac{T_S}{T_D}$$

$n = \#\textit{of nodes}$ $R = \#\textit{of rounds}$ $G \times G = \textit{grid size}$

Synchronizer Protocol: 2BSYNC

Node 0 $= f_0()$ **Shared Variables:** $\overrightarrow{GV} = GV[0], GV[1]$ **Node 1** $= f_1()$

Use barrier variables: b_0, b_1 ***Initialized to*** 0

$\overrightarrow{GV}_0, b_0$

$b_0 := b_0 + 1$
$b_0!$
$Barr_0$

$GV_0[0] = f_0(\overrightarrow{GV_0})$

$b_0 := b_0 + 1$
$(GV_0[0], b_0)!$
$Barr_0$

$\overrightarrow{GV}_1, b_1$

$b_1 := b_1 + 1$
$b_1!$
$Barr_1$

$GV_1[1] = f_1(\overrightarrow{GV_1})$

$b_1 := b_1 + 1$
$(GV_1[1], b_1)!$
$Barr_1$

Atomic Send. Either both $GV_0[0]$ and b_0 are received, or none is received. Can be implemented on existing network stack, e.g, TPC/IP

$Barr_0 \equiv while(b_1 < b_0)\ \ skip;$

Proof of correctness in paper

Tool Overview

Project webpage (http://mcda.googlecode.com)

- Tutorial (https://code.google.com/p/mcda/wiki/Tutorial)

Verification

- daslc --nodes 3 --seq --rounds 3 --seq-dbl --out tutorial-02.c tutorial-02.dasl
- cbmc tutorial-02.c (takes about 10s to verify)

Code generation & simulation

- daslc --nodes 3 --madara --vrep --out tutorial-02.cpp tutorial-02.dasl
- g++ …
- mcda-vrep.sh 3 outdir ./tutorial-02 …

DEMO

Future Work

Improving scalability and verifying with unbounded number of rounds

Verifying for unbounded number of nodes (parameterized verification)

- Paper at SPIN'2014 Symposium

Asynchronous and partially synchronous network semantics

Scalable model checking

- Abstraction, compositionality, symmetry reduction, partial order reduction

Fault-tolerance, uncertainty, …

- Combine V&V of safety-critical and mission-critical properties

Contact Information Slide Format

Sagar Chaki
Principal Researcher
SSD/CSC
Telephone: +1 412-268-1436
Email: chaki@sei.cmu.edu

U.S. Mail
Software Engineering Institute
Customer Relations
4500 Fifth Avenue
Pittsburgh, PA 15213-2612
USA

Web
www.sei.cmu.edu
www.sei.cmu.edu/contact.cfm

Customer Relations
Email: info@sei.cmu.edu
Telephone: +1 412-268-5800
SEI Phone: +1 412-268-5800
SEI Fax: +1 412-268-6257

Synchronous Collision Avoidance Code

```
MOC_SYNC;

CONST X = 4; CONST Y = 4;
CONST NEXT = 0;
CONST REQUEST = 1;
CONST WAITING = 2;
CONST MOVE = 3;

EXTERN int
MOVE_TO (unsigned char x,
         unsigned char y);

NODE uav (id) { … }

void INIT () { … }

void SAFETY { … }
```

```
NODE uav (id)
{
  GLOBAL bool lock [X][Y][#N];
  LOCAL int state,x,y,xp,yp,xf,yf;
  void NEXT_XY () { … }
  void ROUND () {
    if(state == NEXT) { …
      state = REQUEST;
    } else if(state == REQUEST) { …
      state = WAITING;
    } else if(state == WAITING) { …
      state = MOVE;
    } else if(state == MOVE) { …
      state = NEXT;
    } } }
```

```
INIT
{
  FORALL_NODE(id)
    state.id = NEXT;
    //assign x.id and y.id non-deterministically
    //assume they are within the correct range
    //assign lock[x.id][y.id][id] appropriately

  //nodes don't collide initially
  FORALL_DISTINCT_NODE_PAIR (id1,id2)
    ASSUME(x.id1 != x.id2 || y.id1 != y.id2);
}

SAFETY {
  FORALL_DISTINCT_NODE_PAIR (id1,id2)
    ASSERT(x.id1 != x.id2 || y.id1 != y.id2);
}
```

Synchronous Collision Avoidance Code

```
if(state == NEXT) {
  //compute next point on route
  if(x == xf && y == yf) return;
  NEXT_XY();
  state = REQUEST;
} else if(state == REQUEST) {
  //request the lock but only if it is free
  if(EXISTS_OTHER(idp,lock[xp][yp][idp] != 0)) return;
  lock[xp][yp][id] = 1;
  state = WAITING;
} else if(state == WAITING) {
  //grab the lock if we are the highest
  //id node to request or hold the lock
  if(EXISTS_HIGHER(idp, lock[xp][yp][idp] != 0)) return;
  state = MOVE;
}
```

```
else if(state == MOVE) {
  //now we have the lock on (xp,yp)
  if(MOVE_TO()) return;
  lock[x ][y][id] = 0;
  x = xp; y = yp;
  state = NEXT;
}
```